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The determination of cloud pressures from rotational Raman scattering in satellite backscatter ultraviolet measurements

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Abstract. We have retrieved cloud pressures with the Nimbus 7 solar backscatter ultraviolet spectrometer and total ozone mapping spectrometer by utilizing properties of rotational Raman scattering. The retrieved cloud pressures are compared with coincident cloud pressures derived from the temperature humidity infrared sounder, as well as climatological cloud pressures from the International Satellite Cloud Climatology Project. Results show good agreement between cloud pressures measured using ultraviolet and infrared techniques, although a small bias is present. The bias in cloud pressures is likely due in part to different radiative properties of clouds at ultraviolet and infrared wavelengths. The ultraviolet measurements described here are sensitive to cloud optical thickness, while infrared measurements are sensitive to cloud top temperature. Ultraviolet cloud pressure measurements combined with measurements from other spectral regions may therefore provide information about cloud type. Cloud pressures measured by means of ultraviolet scattering properties will be more appropriate for use in satellite backscatter ultraviolet ozone retrieval algorithms. We suggest ways in which future ultraviolet remote sounding instruments may be designed to more optimally measure cloud pressure.

Introduction

When incoming solar radiation is Rayleigh scattered in the Earth's atmosphere, a fraction of the photons are scattered at wavelengths shifted from the incident wavelength because of rotational Raman scattering. The effect of rotational Raman scattering, henceforth referred to as RRS and also known as the Ring effect, is to cause depletion or filling in of solar Fraunhofer lines in the Earth's backscattered ultraviolet (buv) spectrum. The amount of depletion or filling in due to RRS is roughly proportional to the average number of times the incoming solar radiation is Rayleigh scattered before it reaches a satellite-borne instrument [e.g., *Joiner et al.*, 1995]. This property of RRS can be used to deduce a cloud pressure, because the average number of Rayleigh scatterings is related to cloud pressure. A cloud in the ultraviolet can be modeled as a highly reflecting surface. As the pressure of the reflecting surface decreases (or altitude increases), the average number of times a photon is Rayleigh scattered before reaching the satellite also decreases.

Ozone-insensitive ultraviolet wavelengths are not sensitive to cloud pressure using traditional radiative transfer calculations. Ozone-sensitive wavelengths are sensitive to ozone above a cloud. In the presence of clouds, total ozone retrieval algorithms add to the observed ozone above the clouds an amount of ozone assumed to be present below the clouds. Underestimating cloud pressure will therefore result in an overestimate of the ozone under the cloud and thus an overestimate in total ozone. Therefore it is important to use an accurate estimate of cloud pressure in buv ozone retrieval algorithms. The use of rotational Raman scattering properties provides one of the few means of measuring cloud pressures with satellite ultraviolet spectrometers.

The use of RRS to determine cloud pressures in planetary atmospheres has been suggested previously [e.g., *Brinkman*, 1968; *Wallace*, 1972]. Information about aerosol haze in the Jovian planet atmospheres has been derived from RRS [e.g., *Price*, 1977]. *Park et al.* [1986] derived cloud pressures in the Earth's atmosphere from RRS using Nimbus 7 solar backscatter ultraviolet (SBUV) continuous spectral scan measurements. Their retrieved cloud pressures were compared

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with those from the Nimbus 7 temperature humidity infrared (THIR) sounder. The results showed an apparent relationship between the filling in due to RRS and cloud pressure. However, because only a small number of data points were examined, the results were somewhat inconclusive.

Differences in cloud pressures derived by infrared and ultraviolet measurements are expected, because IR and UV radiances are affected differently by clouds. Thermal infrared measurements are sensitive to cloud top temperature. Ultraviolet measurements are more sensitive to cloud volume because of scattering and are therefore expected to give higher effective cloud pressures. Because UV cloud pressure measurements are more sensitive to cloud optical thickness than IR measurements, combined UV and IR measurements may provide information about cloud type.

In this paper, methodology for retrieving effective ultraviolet cloud pressures is described. Then, cloud pressures are retrieved using observations from the Nimbus 7 SBUV (continuous scan mode) and total ozone mapping spectrometer (TOMS). The SBUV- and TOMS-retrieved cloud pressures are compared with coincident cloud pressures derived from the Nimbus 7 THIR. The SBUV average cloud pressures are also compared with climatology from the International Satellite Cloud Climatology Project (ISCCP) and THIR. Next, we give several explanations for observed differences in cloud pressures obtained by different techniques, and discuss potential advantages of the UV technique presented here. Finally, we suggest ways in which the ultraviolet cloud pressure measurement technique may be optimized for future sounding instruments.

Method

The backscattered ultraviolet (buv) radiance I in terms of a Lambert-equivalent reflectivity model (neglecting RRS) is given by

$$I(\mu, \mu_o, R, \Omega, P_c) = I_o(\mu, \mu_o, R=0, \Omega, P_c) + \frac{R\, I_g(\mu_o, \Omega, P_c)\ \gamma(\mu, \Omega, P_c)}{1 - RS_b(\Omega, P_c)}, \quad (1)$$

[*Dave*, 1964], where I_o is the radiation backscattered by the atmosphere, R is the Lambert-equivalent reflectivity, I_g is the sum of the direct and diffuse radiation reaching the surface, γ is the transmittance of the reflected radiation in the direction of the satellite, S_b is the fraction of the reflected radiance scattered back to the surface by the atmosphere, μ_o and μ are the cosines of the solar zenith angle and satellite zenith angle, respectively, Ω is total ozone, and P_c is cloud pressure. *Bhartia et al.* [1993] have shown that cloud effects on buv measurements at ozone-insensitive wavelengths can be modeled accurately using the concept of Lambert-equivalent reflectivity. Mie scattering is implicitly taken into account by simply increasing or decreasing the surface reflectivity. Rayleigh scattering between cloud layers and between cloud and ground is not explicitly accounted for in this model. Enhanced Rayleigh scattering can be implicitly accounted for by increasing P_c.

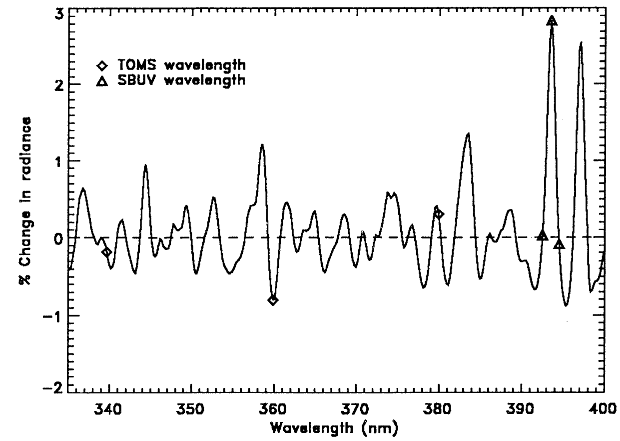

Figure 1. Computed percent change in radiance due to rotational Raman scattering at solar zenith angle 30° (solid line) and pressure 1000 mbar. Diamonds and triangles indicate wavelengths used for cloud pressure retrievals.

The effect of RRS on satellite backscatter ultraviolet measurements has been accurately modeled by *Joiner et al.* [1995]. Figure 1 shows the computed filling in and depletion due to RRS using this model as a function of wavelength from 340 to 400 nm at the TOMS and SBUV spectral resolution of approximately 1 nm. Ozone absorption is negligible at these wavelengths. The largest filling in effects are at the calcium K and H Fraunhofer lines at 393.5 and 396.9 nm, respectively. The computed RRS effects agree well with observations from the SBUV continuous scan mode and the shuttle-borne SBUV/2 (SSBUV) sweep mode [*Joiner et al.*, 1995]. Also indicated in Figure 1 are SBUV wavelengths and TOMS wavelengths that will be used to derive effective ultraviolet cloud pressures as described below. Again, these wavelengths are not significantly affected by ozone absorption.

Because the SBUV continuous scan mode makes measurements over the entire spectral range from 200-400 nm, we can utilize the large RRS signal at the calcium K Fraunhofer line. Figure 2 shows the predicted percent change in radiance at 393.5 nm as a function of effective ultraviolet cloud pressure for several different solar zenith angles. The curves in Figure 2 were computed using the full radiative transfer model described by *Joiner et al.* [1995]. The percent change in radiance is approximately linear with cloud pressure at solar zenith angles less than 70°.

At least two wavelengths are needed to distinguish between the effects of reflectivity and rotational Raman scattering that depends on P_c. *Joiner et al.* [1995] measured RRS effects at the Ca K Fraunhofer line using

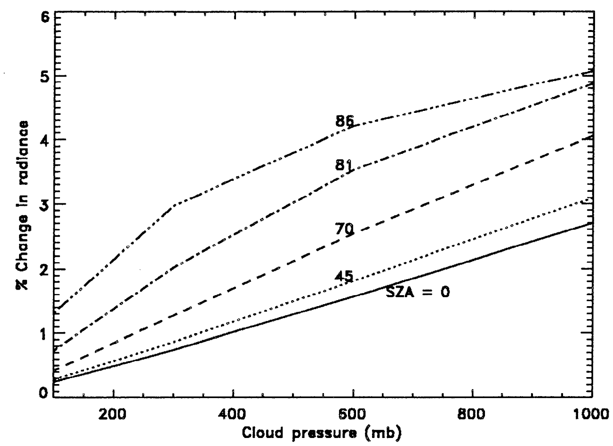

Figure 2. Percent change in radiance due to rotational Raman scattering as a function of cloud pressure for several solar zenith angles computed at $\lambda = 393.5$ nm and $R = 70\%$ at nadir.

three wavelengths: the center of the Ca K line (393.52 nm) and either side of the Ca K line in the continuum (392.52 and 394.52 nm). These wavelengths are indicated in Figure 1 and will be used to derive cloud pressures here. The change in radiance, or filling in, due to RRS is simply the radiance (normalized to unit solar flux) at the center of the calcium line divided by the average radiance of the two continuum wavelengths. Then, cloud pressure can be simply derived using the curves in Figure 2. Because SBUV makes measurements one wavelength at a time, the instrument field of view changes slightly during the time in which the instrument scans the Ca K line. The use of three wavelengths removes the effects of scene changes that are linear with time (wavelength). The filling in effect varies slightly with reflectivity. Because the reflectivity dependence of the filling in effect is small compared with the cloud pressure and solar zenith angle dependence [*Joiner et al.*, 1995], we did not attempt to account for it.

SSBUV results reported by *Joiner et al.* [1995] indicated that, as predicted, the amount of filling in due to RRS decreased with increased reflectivity or cloud fraction. However, because of a low signal-to-noise ratio (resulting from the inability to completely correct for scene changes) and a relatively small sample size, it was not possible to accurately determine and validate cloud pressures from those observations. Similar difficulties occur in validating cloud pressures retrieved from SBUV continuous scan mode observations because of the relatively small number of observations and coarse spatial coverage. The SBUV instrument operated in continuous scan mode about 1 day per month between 1979 and 1986 with approximately 300 complete spectral scans per day.

Although not optimal for retrieving cloud pressures, TOMS provides a much larger number of observations than SBUV in continuous scan mode. For example, there are more TOMS observations in a single day than in the entire SBUV continuous scan record. The TOMS field of view is approximately 50 km, as compared with the SBUV 200-km field of view. TOMS consists of six channels at wavelengths 312.3, 317.4, 331.1, 339.7, 359.9, and 380.0 nm. The three shortest TOMS wavelengths are sensitive to total ozone, while the three longest wavelengths are relatively insensitive to ozone. Fortunately, for the purpose of retrieving cloud pressures, the 360 nm TOMS channel is sensitive to rotational Raman scattering, as indicated in Figure 1. Unlike SBUV, TOMS makes nearly simultaneous measurements at its six discrete wavelengths. Because the TOMS channels are spaced far apart in wavelength, spectral properties of the reflectivity are important. We use the 340-, 360-, and 380-nm channels to solve simultaneously for R, P_c, and one additional parameter related to the spectral dependence of R. We assume a linear wavelength dependence in R, that is, $R(\lambda) = R_0 + R_1\Delta\lambda$, where $\Delta\lambda = (380 - \lambda)/40$, and the wavelength λ is in nm. This assumption is appropriate on the basis of modeling results that show a linear wavelength dependence of the effective reflectivity of clouds (in terms of the Lambertian-equivalent model) using a full Mie scattering calculation (Ahmad et. al., The effect of thin clouds on ozone retrieval from the buv technique, submitted to *Journal of Geophysical Research*, 1994, hereinafter referred to as Ahmad et. al., submitted manuscript, 1994). Any deviation from the assumed linear $R(\lambda)$ dependence will produce an error in the TOMS cloud pressure retrieval.

The radiance sensitivity to cloud pressure for the TOMS channels is computed as in Figure 2 at the appropriate TOMS wavelengths. In the TOMS cloud pressure retrieval, we neglect the scan angle dependence that is relatively small. We also ignore absorption by O_2-O_2 that has weak bands near 360 and 380 nm. The change in radiance resulting from O_2-O_2 absorption was computed by *Joiner et al.* [1995] and is expected to be smaller than that resulting from RRS at the TOMS wavelengths.

The effect of instrument noise on the cloud pressure retrieval can be estimated from Figure 2. The instrument noise of SBUV in continuous scan mode has a standard deviation of approximately 1% at a given wavelength. At a solar zenith angle of 45°, for example, a 1% error in radiance will result in an error of approximately 300 mbar in cloud pressure. The filling in at the Ca K line used in SBUV cloud pressure retrievals is approximately 3 times as great as the depletion at the 360-nm TOMS channel, but the SBUV instrument noise is about 3 times higher than that of TOMS as a result of the shorter integration time. Therefore the signal-to-noise ratio of the TOMS cloud pressure measurement is approximately the same as that of the SBUV measurement. The signal-to-noise ratio of the TOMS measurement can, however, be slightly increased by spatial averaging or gridding of individual spots.

Results and Comparisons With Other Measurements

Two kinds of comparisons are made between our derived ultraviolet cloud pressures and infrared cloud top pressure measurements. The first type of comparison is made between colocated UV and IR cloud pressure measurements. For this comparison, UV cloud pressure measurements from the SBUV and TOMS instruments are compared with THIR-measured cloud top pressures. All three instruments flew on the Nimbus 7 satellite. The second type of comparison is made on a climatological basis. This comparison involves averaged SBUV cloud pressure measurements and climatology from the ISCCP and THIR data sets.

When comparing IR- and UV-derived cloud pressures, we must carefully consider effects related to cloud detection, cloud amount, and cloud radiative properties [e.g., *Rossow et al.*, 1989]. In the following comparisons with THIR data, we consider only scenes with UV reflectivities greater than 40% (i.e., high-UV optical depth) unless stated otherwise. By using high-reflectivity scenes, cloud types that affect infrared and do not affect ultraviolet radiation, such as thin cirrus, are not included in the comparison. In the subsequent SBUV comparison with ISCCP, we have used average ISCCP cloud pressures including all cloud types [Rossow and Schiffer, 1991]. This monthly mean ISCCP climatology (including all cloud types) is the one used in the latest version (version 7) of the TOMS ozone retrieval algorithm. Because the ISCCP climatology includes all cloud types, we might expect larger differences between ultraviolet and ISCCP cloud pressures than between ultraviolet and THIR cloud pressures. We assume that in a given cloudy pixel, the scene is completely cloud covered. We note that infrared and ultraviolet cloud radiative properties are different and that systematic errors in both infrared and ultraviolet retrievals may exist as a result of inaccurate modeling of cloud radiative properties.

Figure 3 is a scatter diagram of SBUV-measured cloud pressures versus coincident THIR-measured cloud top pressures. The data shown here comprise all SBUV continuous scan measurements in 1979 with reflectivity greater than 40% between 55°N and 55°S latitude. The THIR retrieval algorithm that produced the results shown here was not the final THIR algorithm. The final THIR algorithm produced the archived Nimbus 7 cloud products stored on the more coarse Earth Radiation Budget (ERB) grid. The main difference between the final THIR algorithm and the one used here is the temperature profile used to define the background radiance. The THIR retrieval algorithm that produced the results shown here utilized climatological temperature profiles, whereas the final THIR algorithm used temperature profiles from the Air Force three-dimensional nephanalysis [*Hwang et al.*, 1988]. The THIR measurements are averaged in 1°× 1° bins and are compared with a single SBUV continuous scan measurement. The SBUV-retrieved cloud pressures are in general higher than those measured with THIR. The correlation between SBUV and THIR cloud pressures is 0.62. The standard deviation about the line of agreement is 214 mbar, and the standard deviation about the second-order polynomial fit is 155 mbar.

Next, we compare SBUV average cloud pressures with climatology from ISCCP and THIR. Figure 4 shows a cross section of retrieved cloud pressures at longitude 92.5°E as a function of latitude. The SBUV cloud pressures shown here constitute an average of all SBUV continuous scans from 1979 to 1986 with reflectivities greater than 40% averaged in 5°× 5° bins. Also shown along with the terrain pressure is the ISCCP climatology and a zonal climatology derived from THIR measurements given by $P_{\mathrm{THIR\ clim}} = 300 + 150[1 - \cos(2 \times \mathrm{lat})]$ mbar [e.g., *McPeters et al.*, 1993]. The SBUV results reproduce features in the ISCCP climatology such as the north-south asymmetry, low cloud pressures in the tropics, and relatively high cloud pressures in the southern midlatitudes. It should be noted that the average number of SBUV points in a bin is relatively low (approximately 3 points/bin at low latitudes and 10 points/bin at high latitudes).

In both Figures 3 and 4, the SBUV-retrieved cloud pressures are slightly higher than the THIR-colocated cloud pressures and the ISCCP and THIR climatological cloud pressures. The higher SBUV cloud pressures are expected, because the UV technique is sensitive to Rayleigh scattering, whereas the IR technique is sensitive to the cloud top temperature. At a UV reflectivity of 40%, more than 60% of the radiation penetrates the cloud top. Some of this radiation is scattered back toward the satellite after being Rayleigh scattered within and below the cloud. Therefore the retrieved UV cloud

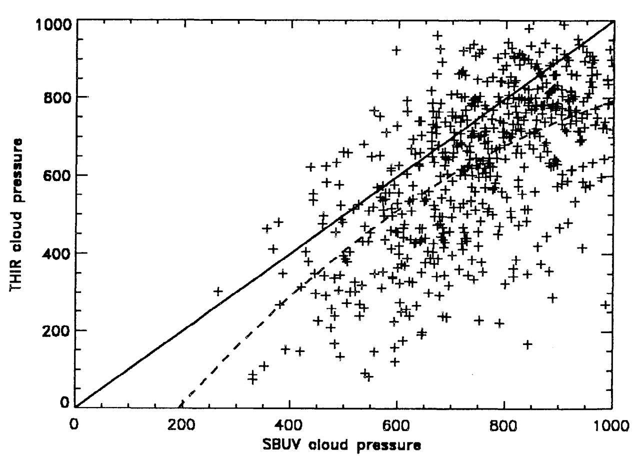

Figure 3. Scatter diagram of solar backscatter ultraviolet (SBUV)-retrieved cloud pressure versus temperature humidity infrared (THIR)-retrieved cloud pressure in 1979 for reflectivities greater than 40%. Solid line is the line of perfect fit and dashed line is a least squares second-order polynomial fit.

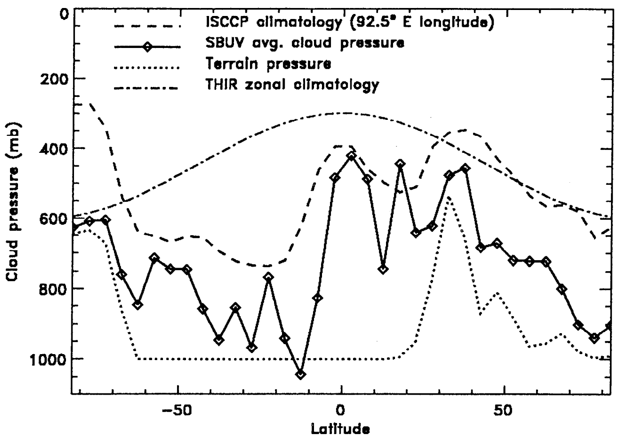

Figure 4. Retrieved average cloud pressure for reflectivities greater than 40% from SBUV at longitude 92.5±2.5°E with average climatological cloud pressure from the International Satellite Cloud Climatology Project (ISCCP), THIR zonal climatology, and terrain pressure for comparison.

pressure will be higher than the physical cloud top pressure.

When we examined cloud or scene pressures over Antarctica in more detail, we found that the average cloud/scene pressure was approximately equal to the terrain pressure. Figure 5 is similar to Figure 4 but shows a cross section through 82.5°S latitude. The SBUV-retrieved cloud/scene pressure follows the terrain pressure closely. Similar results were obtained at different latitudes over Antarctica. The UV reflectivity cannot be used to distinguish clouds from highly reflecting ice. Therefore the derived "cloud" pressure over ice is actually an effective scene pressure, that is, the average of the terrain pressure and cloud pressure weighted by cloud amount. Therefore it is not valid to compare SBUV-retrieved scene pressures with ISCCP cloud pressures. By using the cloud fraction provided in the ISCCP database, an effective ISCCP scene pressure can be derived and is shown in Figure 5. THIR results were not reliable over Antarctica and are not shown.

The small difference between the SBUV and ISCCP scene pressures over Antarctica is probably due to a combination of several errors. One source of error in the ISCCP scene pressure results from a lack of thermal contrast in the IR that prevents IR techniques from detecting high-pressure clouds. Therefore the ISCCP results over Antarctica are probably biased toward low-pressure clouds (W. B. Rossow, private communication, 1994). The ISCCP average cloud pressures are also in general very low (above the 400-500 mbar polar tropopause) and may be unrealistic. The UV technique may be relatively insensitive to polar clouds that are optically thin because of the extremely dry conditions over Antarctica. This will tend to bias the UV results toward the surface. The UV radiative transfer model does not account for excess scattering between the bright surface and cloud base that will increase scene pressure. Excess scattering between a cloud base and the bright surface may produce an effective scene pressure that is greater than the terrain pressure. Ahmad et. al. (submitted manuscript, 1994) have discussed the enhanced scattering effect that also enhances ozone absorption between clouds and surface.

We next compare cloud pressures retrieved with the TOMS instrument, which has a smaller field of view and better spatial coverage than SBUV, with colocated THIR measurements. For this comparison, we examine a single day of TOMS coverage (October 12, 1979) and average the cloud pressures in $1° \times 1°$ bins. Figure 6 is a scatter diagram of the cloud pressures retrieved by TOMS versus those retrieved by THIR for $R > 70\%$. The standard deviation about the second-order polynomial fit is 131 mbar. The standard deviation about the line of agreements is 257 mbar, and the correlation is 0.80. Slightly lower correlations are obtained when the minimum reflectivity of the sample is reduced. For example, the correlation for a sample with $R > 40\%$ is 0.68, which is comparable to the SBUV-THIR correlation for scenes with $R > 40\%$.

As with the SBUV results, the cloud pressures derived from TOMS are in general greater than those measured by THIR, especially for high-pressure clouds. This result is probably due to enhanced Rayleigh scattering within and below clouds as described above. The somewhat better TOMS-THIR agreement, as compared with the SBUV-THIR agreement, may be due in part to a higher signal-to-noise ratio in the TOMS measurements (enhanced by averaging scenes) and also to better coalignment between the TOMS and THIR fields of view.

Figure 7 is a cross section through 40.5°N latitude of retrieved UV cloud pressures from TOMS on the

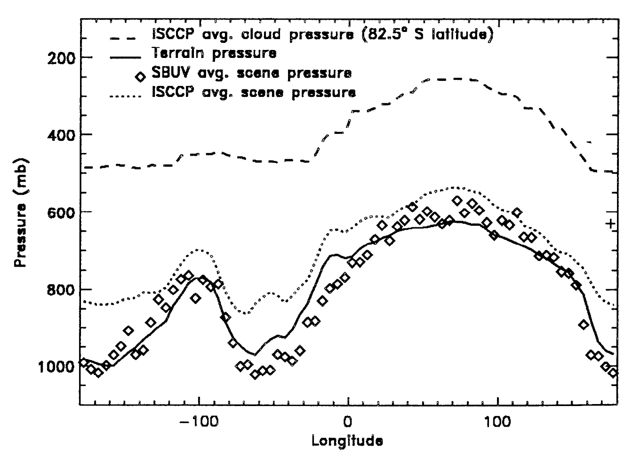

Figure 5. Retrieved average scene pressure from SBUV over Antarctica at latitude 82.5±2.5°S, with average terrain pressure, ISCCP average cloud pressure, and ISCCP average scene pressure for comparison.

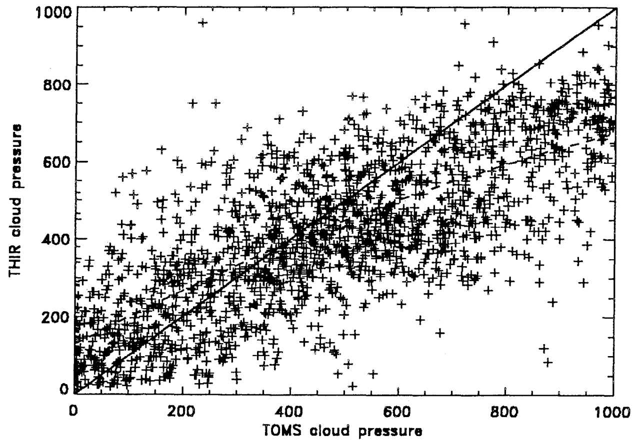

Figure 6. Similar to Figure 3 with TOMS-retrieved cloud pressure versus THIR-retrieved cloud pressure for reflectivities greater than 70%.

same day as above with a 4° running average applied to smooth the data. Also shown are colocated THIR measurements. A large dynamic range of cloud pressures is measured by both TOMS and THIR. High-pressure (low-altitude) clouds are retrieved by both TOMS and THIR off the western coast of North America (at longitude near 130°W). Similar retrievals of high-pressure clouds from both TOMS and THIR were obtained off the coast of South America and over marine stratocumulus clouds in the south Atlantic. Figure 8 shows a similar cross section through 10.5°N latitude that includes all scenes with reflectivities greater than 30%. At this latitude, low-pressure clouds are retrieved in the intertropical convergence zone. Variability in the low-pressure clouds is observed with both TOMS and THIR. Also shown for comparison are ISCCP climatological cloud pressures. Significant variations from ISCCP climatological cloud pressures are observed.

Some of the differences between TOMS and THIR cloud pressures in Figures 7 and 8 appear to be systematic in contrast with random errors expected from instrument noise. Because systematic errors in the retrieved THIR cloud pressures occur when the temperature profile differs significantly from climatology, systematic differences between the two cloud pressure measurements are expected. We estimate the accuracy of the THIR cloud pressures shown here to be about ±200 mbar.

Discussion

Differences between ultraviolet and infrared cloud pressures may be due to systematic errors in either the IR- or UV-retrieved cloud pressures. Systematic errors in the THIR- or ISCCP-retrieved cloud pressures may result from the use of an incorrect temperature profile, the inability of the infrared to measure high-pressure clouds accurately, or the use of an incorrect cloud fraction. Systematic errors in the SBUV- and TOMS-retrieved cloud pressures may result from errors in the RRS calculation. Additional errors in the TOMS-retrieved cloud pressures may be due to scan angle effects, nonlinearity in $R(\lambda)$, channel-to-channel calibration error, or effects of O_2-O_2 absorption.

When comparing cloud pressures obtained by ultraviolet and infrared measurements, we must consider the different radiative properties of clouds. Infrared cloud pressure is usually defined as the pressure at which the cloud is opaque. For high optical depth clouds, the infrared cloud pressure is approximately equal to the physical cloud top pressure. In contrast, ultraviolet cloud pressures, derived using RRS effects, are more sensitive to cloud volume than infrared measurements. For example, Raman-Rayleigh scattering can be enhanced within clouds, between cloud layers, or in the atmosphere between the Earth's surface and a reflecting cloud base. Because these enhancements of Raman-Rayleigh scattering are not explicitly accounted for in our radiative transfer calculation, our algorithm will retrieve a higher effective cloud pressure under some conditions than the physical cloud top pressure. This ef-

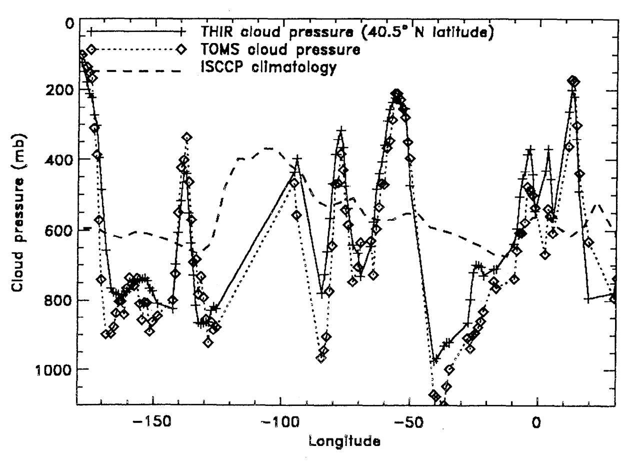

Figure 7. TOMS- and THIR-retrieved cloud pressure on October 12, 1979, at 40.5°N for reflectivities greater than 40% with ISCCP climatology for comparison.

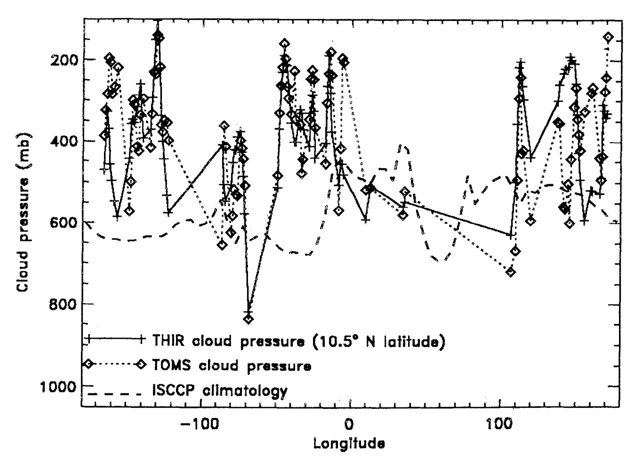

Figure 8. Same as Figure 7 but at 10.5°N latitude for reflectivities greater than 30%.

fect may be particularly important for clouds near the surface where, more enhancement of Raman-Rayleigh scattering may occur. Both the SBUV and TOMS observations support this conjecture.

There are other indications that cloud pressures derived from IR-visible measurements are lower than those derived from ultraviolet measurements. *Thompson et al.* [1993] found a correlation between version 6 TOMS total ozone and reflectivity in the south Atlantic over marine stratocumulus clouds. The climatological cloud pressures used in the version 6 algorithm were significantly underestimated in this region, and it has been shown that TOMS measures anomalously high ozone over low-altitude clouds [*Hudson and Kim*, 1994]. *Thompson et al.* [1993] derived a correction factor for total ozone on the basis of THIR cloud pressure measurements. They used the correction factor with ISCCP daily cloud pressures to correct the TOMS version 6 total ozone in 1989 over the south Atlantic. However, even after applying the correction, a significant correlation between retrieved total ozone and reflectivity still remained. One explanation given was that the correction was not great enough, implying that the ISCCP cloud pressures were too low for this application. The TOMS results obtained here over south Atlantic marine stratocumulus clouds (not shown in figures) also suggest that ultraviolet cloud pressures are higher than infrared-derived cloud pressures.

We expect differences between the SBUV and climatological cloud pressures as the result of sampling effects, as well as cloud radiative effects. The relatively large SBUV field of view likely excluded many partially cloudy scenes from the sample, resulting in a lower cloud fraction. The average SBUV cloud fraction (fraction of cloud scenes with reflectivities greater than 40%) between 55°S and 55°N latitude was approximately 20%. This cloud fraction is approximately a factor of 3 lower than the average ISCCP cloud fraction and indicates that a significant fraction of clouds has been excluded from the SBUV sample. It is also likely that low-UV optical depth clouds are included in the ISCCP sample and excluded from the SBUV sample. The comparison between UV and IR cloud pressures in Figures 3 and 6 included only high-UV optical depth clouds, and the same bias between UV and IR cloud pressures is present. This result indicates that much of the difference between IR and UV cloud pressures is likely due to cloud radiative effects rather than sampling effects.

Because biases appear between infrared and ultraviolet cloud pressure measurements does not necessarily mean that one is more correct than the other. The use of one or the other cloud pressure measurement may be more appropriate for a given application. For example, when computing outgoing long-wave radiation, infrared cloud pressure is the more relevant quantity. However, when assessing the impact of clouds on atmospheric scattering as applied to buv ozone retrievals, effective ultraviolet cloud pressure is the more appropriate quantity.

Despite differences in the radiative effect of clouds in different spectral regions, a comparison between ultraviolet and infrared cloud pressures has provided some validation of the retrieved ultraviolet cloud pressures. Although there is a bias between infrared and ultraviolet cloud pressures, the agreement between the derived cloud pressures is good, especially when only high-UV optical depth clouds are included in the sample.

The ultraviolet cloud pressure measurement technique presented here has advantages over infrared measurements in some instances. Because the infrared measures cloud top temperature, not cloud top pressure, errors in the derived infrared cloud top pressure may be introduced by the use of an incorrect temperature profile or surface skin temperature. For example, errors in derived infrared cloud pressures can occur in the presence of a temperature inversion. Errors can also occur if there is a small thermal contrast between the atmosphere and surface (i.e., clouds near the surface) or if the surface skin temperature is much higher than the atmospheric temperature. Under these conditions, the ultraviolet technique may provide a more accurate cloud pressure measurement.

The UV method of determining cloud optical thickness may be less prone to errors than traditional methods using visible reflectivity. Cloud shadowing effects, leakage of radiation from sides of clouds, and other geometric effects may result in a large variability in visible cloud reflectivity, even for relatively homogeneous clouds. The UV technique may be less affected by these problems, because it relies on a relative radiance difference between two or more channels rather than absolute radiance, as in visible techniques. For the same reason, the UV technique will also be less prone to errors caused by calibration drifts.

The results shown here are complementary to other comparisons of cloud pressures measured by different techniques. For example, *Liao et al.* [1994a, b] have compared ISCCP cloud pressures with cloud top pressures derived from the Stratospheric Aerosol and Gas Experiment II (SAGE II) occultation measurements. They found that SAGE II and ISCCP cloud pressures agreed for clouds with distinct tops. However, the SAGE II measured lower cloud pressures for clouds with diffuse tops. Because of the long horizontal path, SAGE II measurements are more sensitive to clouds with very low optical thicknesses. The ultraviolet technique used here probes deeper into clouds than either the SAGE II or infrared-visible measurement. Therefore the UV measurements provide an additional piece of information about cloud volume.

Conclusions

We have demonstrated that cloud pressures can be measured at ultraviolet wavelengths by making use of rotational Raman scattering properties. The cloud pressures derived from TOMS and SBUV observations show good agreement with cloud pressures measured simultaneously in the infrared by THIR. Reasonable agreement was also obtained between average SBUV cloud pressures and climatological cloud pressures from ISCCP. Differences between IR- (IR-visible) and UV-retrieved cloud pressures are likely due in part to the different radiative effect of clouds at infrared and ultraviolet wavelengths. Because the different cloud pressure measurement techniques provide different information about cloud properties, a better understanding of clouds may be obtained by studying cloud multispectral properties. For instance, using the complementary information embedded in infrared and ultraviolet radiances, it may be possible to distinguish stratiform from cumulus clouds. Further study is needed to compare ultraviolet cloud pressure measurements with other cloud pressure measurements on a climatological basis.

The TOMS and SBUV instruments were not designed to measure cloud pressures and are not optimal for the task. The UV-retrieved cloud pressures shown here have a relatively low signal-to-noise ratio, and the TOMS measurements may be affected by other systematic effects. Despite these problems, reasonable results were obtained with the UV technique. Future sounding instruments can be designed to improve upon the results shown here in several ways. The assets of the SBUV spectral scan measurements and TOMS measurements could be combined to optimize the retrieval of cloud pressures. For example, optimized discrete channels could be selected for a TOMS-type instrument, such as the three wavelengths centered around the Ca K line used here in SBUV retrievals. The relatively high signal-to-noise ratio of a TOMS-type measurement and the ability to make simultaneous measurements at several discrete wavelengths will significantly increase the signal-to-noise ratio over that of an SBUV-type measurement.

Finally, the RRS filling in effect (and thus the signal-to-noise ratio for cloud pressure retrievals) will be greater at higher spectral resolution. For example, *Joiner et al.* [1995] showed that decreasing the spectral bandpass from 1 nm to 0.2 nm increases the filling in at the Ca K line by a factor of more than 3. At 0.2 nm spectral resolution, and with the present TOMS instrument noise, the signal-to-noise ratio would be increased by about an order of magnitude over the present observations, resulting in a precision of about 30 mbar.

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